CHAPTER 5.

Tree Mortality

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INTRODUCTION

Tree mortality is a natural process in all forest ecosystems. High mortality can be an indicator of forest health problems. On a regional scale, high mortality levels may indicate widespread insect or disease impacts or stress from large-scale regional weather events, such as severe droughts. High mortality may also occur if a large proportion of the forest in a particular region is made up of older, senescent stands. The approach presented here seeks to detect mortality patterns that might reflect changes to ecosystem processes at large scales. In many cases, the proximate cause of mortality may be discernable. Understanding proximate causes of mortality ***may*** provide insight into whether the mortality is within the range of natural variation or reflects more fundamental changes to ecological processes.

DATA

Forest Inventory and Analysis (FIA) Phase 2 (P2) data were the basis of the mortality analysis. The FIA P2 data are collected across forested land throughout the United States, with approximately one plot per 6,000 acres of forest, using a rotating panel sample design (Bechtold and Patterson 2005). Field plots are divided into spatially balanced panels, with one panel being measured each year. A single cycle of measurements consists of measuring all panels. This "annualized" method of inventory was adopted, State by State, beginning in 1999. The cycle length (i.e., number of years required to measure all plot panels) ranges from 5 to 10 years.

An analysis of mortality requires data collected at a minimum of two points in time. Therefore, mortality analysis was possible for areas where data from repeated plot measurements using consistent sampling protocols were available (i.e., where one cycle of measurements had been completed and at least one panel of the next cycle had been measured, and where there had been no changes to the protocols affecting measurements of trees or saplings). In this report, as in recent years, the repeated P2 data were available for all of the Central and Eastern States. The most recent cycle of remeasurements for each State was used in this analysis.

In addition, mortality data have become available from parts of the Western United States. In the West, plots are remeasured on a 10-year cycle. Thus, estimates of growth and mortality from the Western States are based on less than a complete cycle of remeasurement. Working from an incomplete cycle of remeasurement, the effective sampling intensity for growth and mortality estimates is significantly lower than FIA's standard of one plot per 6,000 acres (table 5.1). Therefore, the sampling error percentage on growth and mortality estimates tends to be large. Results are not presented for ecoregion sections where fewer than 25 plots had been remeasured or

Table 5.1—Western States from which repeated Forest Inventory and Analysis Phase 2 measurements were available, the time period spanned by the data, and the effective sample intensity (based on the proportion of plots that had been remeasured) in the available datasets

State	Time period	Effective sample intensity
Arizona	2001–2018	one plot: 7,500 acres
California	2001–2017	one plot: 8,571 acres
Colorado	2002–2018	one plot: 8,571 acres
Idaho	2004–2018	one plot: 12,000 acres
Montana	2003–2018	one plot: 10,000 acres
Nevada	2004–2018	one plot: 12,000 acres
New Mexico	2005–2018	one plot: 15,000 acres
Oregon	2001–2017	one plot: 7,500 acres
Utah	2000–2018	one plot: 6,667 acres
Washington	2002–2017	one plot: 10,000 acres
Wyoming[a]	2000–2018	one plot: 7,500 acres

[a] Mortality estimates for Wyoming are based on a comparison of annualized inventory data with data from the final periodic inventory.

where the percentage of error was unacceptably high. Nevertheless, results presented for the West should be viewed as preliminary. Because of this, results from the West are discussed separately from those from the Eastern and Central United States. The division of Eastern/Central versus Western States, as well as the forest cover within those States, is shown in figure 5.1.

METHODS

The Forest Inventory and Analysis program calculates the annual growth, mortality, and removal volume on each plot over the interval between repeated measurements.[1] These values are stored in the FIA Database (version 8.0) (Burrill and others 2018). EVALIDator (ver. 1.8.0.01), an online tool for querying the FIA Database and generating area-based reports on forest characteristics (USDA Forest Service, FIA program 2019), was used to obtain annual gross growth[2] rates and mortality rates over the most recent measurement cycle for each of 113 ecoregion sections (Cleland and others 2007, McNab and others 2007) covering the Eastern and Central United States and 23 ecoregion sections in the Western[3] United States. For most States, the most recent cycle of available data ran through 2018[4] (e.g., data collected from 2012 through 2018).

[1] For a detailed explanation of how FIA calculates annualized growth, mortality, and removals, see Pugh and others (2018).

[2] Gross growth represents the increase in tree volume without adjusting for the volume of trees that died (i.e., mortality volume) in the ecoregion.

[3] At the time that this analysis was being completed, the method for estimating growth in the Interior West was different from that used in the rest of the United States. Because this would lead to results that would not be comparable to those in the rest of the United States, Interior West data were excluded and MRATIOs were only calculated for the West Coast States.

[4] Overall, the most recent data available for any State ranged from 2016 to 2019.

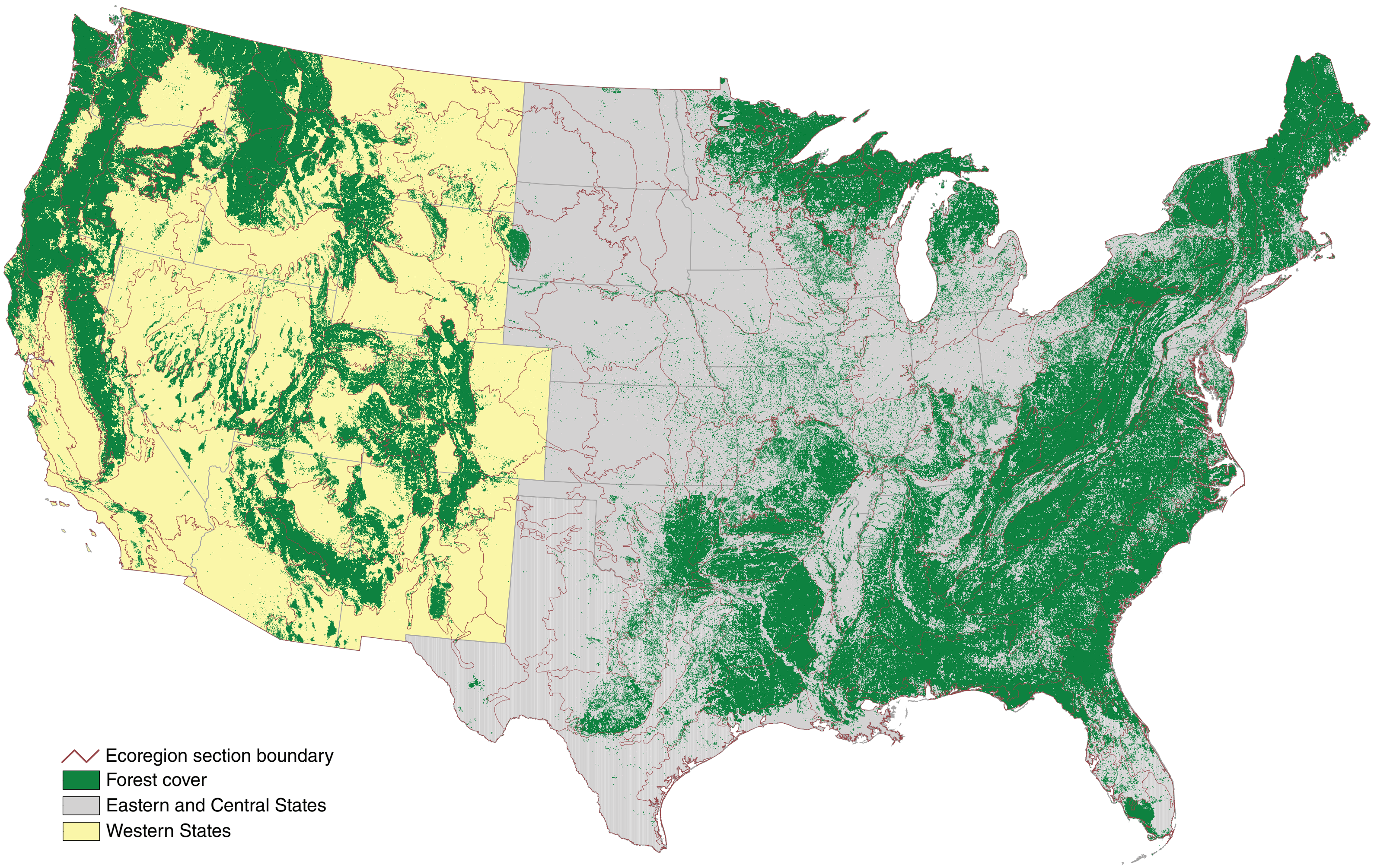

Figure 5.1—Forest cover in the States where mortality was analyzed by ecoregion section (Cleland and others 2007). Mortality in Eastern and Central States was analyzed using a complete remeasurement cycle; in most Western States, mortality was analyzed using a partial cycle of remeasurements, and results there should be considered preliminary. Forest cover was derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (USDA Forest Service 2008).

To compare mortality across forest types and climate zones, the ratio of annual mortality to gross growth (MRATIO) was used as a standardized mortality indicator (Coulston and others 2005). The MRATIO has proven to be a useful indicator of forest health, but it can be a problematic indicator, especially when growth rates are very low. The MRATIO can also be difficult to interpret when there is high uncertainty to growth estimates. Both of these are the case with the data currently available from the West. Therefore, mortality as a percentage of total live volume also was calculated:

$$\text{Mortality percent} = m \,/\, v_1 * 100$$

where

m = annual mortality (cubic feet per year)

v_1 = total live tree volume (cubic feet)

When both this mortality percentage and the MRATIO are high, it suggests a possibly serious forest health concern.

To identify causal agents for the observed mortality, EVALIDator was also used to summarize by the reported "cause of death" associated with the observed mortality. Causes of death are reported as general categories (e.g., insects, fire, weather). For each ecoregion with a high MRATIO, EVALIDator was used to generate a table of annual mortality volume by FIA species group (Burrill and others 2018) and cause of death. From these tables, it is possible to make reasonable assumptions about the particular insects or diseases that may be affecting particular regions. Care must be used in interpreting these causes because tree mortality actually may be caused by a combination of factors (e.g., drought and insects). Further information about the causes of mortality is provided by the aerial survey of insects and disease (see ch. 2 in this report). It is difficult to directly match aerial survey data to mortality observed on FIA plots due to both the difference in timing when mortality is recorded and difficulty matching plot locations with aerial survey mortality polygons. However, aerial survey information has been incorporated into the discussion by referencing State Forest Health Highlights, which reflect in large part the results of aerial surveys.

In addition, mortality rates were derived for each forest type group (Burrill and others 2018, USDA Forest Service 2008) for each ecoregion section. At times, identifying the forest type experiencing high mortality can be more useful than identifying the species group, especially when the cause of death is abiotic.

RESULTS AND DISCUSSION

The MRATIO values are shown in figure 5.2. The MRATIO can be large if an over-mature forest is senescing and losing a cohort of older trees. If forests are not naturally senescing, a high MRATIO (>0.6) may indicate high mortality due to some acute cause (insects or pathogens) or due to generally deteriorating forest health conditions. The ecoregion sections

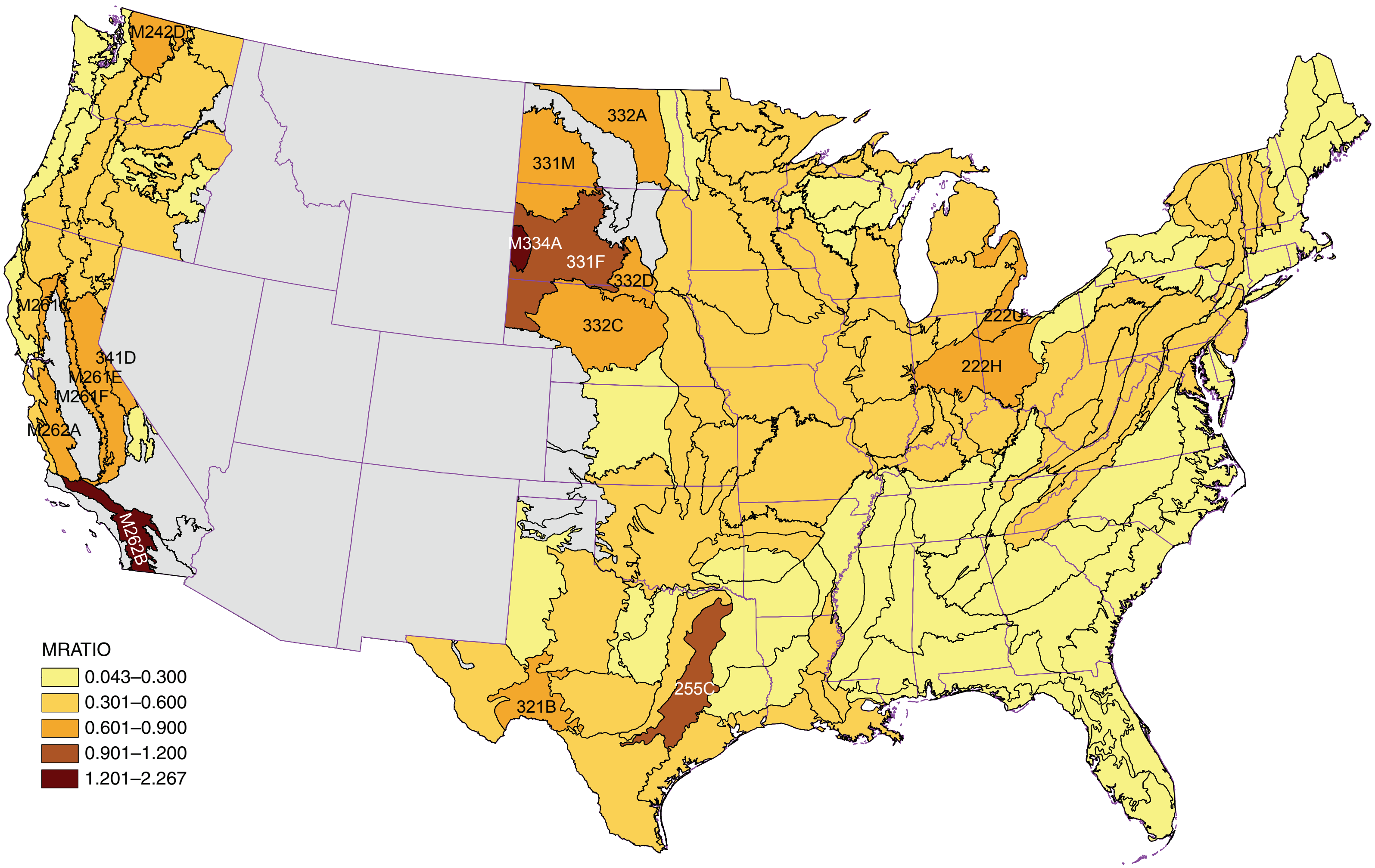

Figure 5.2—Tree mortality expressed as the ratio of annual mortality volume to gross annual volume growth (MRATIO) by ecoregion section (Cleland and others 2007). Data unavailable or insufficient for gray areas. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis program)

with the highest MRATIOs are labeled on the map. In the discussion that follows, the focus is placed on the ecoregions having MRATIOs >0.6.

Eastern and Central States

The highest MRATIOs occurred in ecoregion sections 331F–Western Great Plains (MRATIO = 0.97) in South Dakota and Nebraska and M334A–Black Hills (MRATIO = 1.33). Other areas of high mortality relative to growth on the Great Plains were ecoregion sections 332C–Nebraska Sand Hills (MRATIO = 0.71) and 332D–North-Central Great Plains (MRATIO = 0.70) in South Dakota and Nebraska, 331M–Missouri Plateau (MRATIO = 0.73) in North and South Dakota, and 332A–Northeastern Glaciated Plains (MRATIO = 0.86) in North Dakota. In these Great Plains ecoregion sections where mortality is high relative to growth, the predominant vegetation is grassland. Although the ecoregion sections are quite large, there was relatively little forest land to measure (e.g., 64 forested plots in section 332A and 87 plots in region 331M). In the Plains, tree growth is generally slow because of naturally dry conditions. Where the number of sample plots is small and tree growth is naturally slow, care must be taken in interpreting mortality relative to growth.

In ecoregion section M334A–Black Hills (MRATIO = 1.33), the vast majority (93 percent) of mortality occurred in the ponderosa and Jeffrey pine species group. For the entire ecoregion section, 76 percent of mortality was caused by insects, while 14 percent was caused by fire (table 5.2); for ponderosa (*Pinus ponderosa*) and Jeffrey pine (*P. jeffreyi*), insects and fire were responsible for 74 and 16 percent of mortality, respectively. Mortality in this ecoregion is most likely related to mountain pine beetle (*Dendroctonus ponderosae*). There had been an ongoing pine beetle outbreak in the Black Hills region (Ball and others 2015, 2016; South Dakota Department of Agriculture 2011, 2012, 2013, 2014), though pine beetle activity has declined dramatically in the region since 2015 (Ball and others 2017, Wyoming State Forestry Division 2017). The pine beetle outbreak has ended, but reported mortality remains high because results reported, based on the most recent cycles of FIA data, reflect mortality over the period that includes the peak of the outbreak in 2015.

In ecoregion section 331F–Western Great Plains (MRATIO = 0.97), fire caused 64 percent of mortality; another 19 percent of mortality was weather-related (table 5.2). In this ecoregion section, most of the mortality (about 86 percent) occurred in the ponderosa and Jeffrey pine species group. In this species group, 64 percent of mortality was due to fire and 22 percent was due to adverse weather. Only 7 percent of pine mortality was related to insects.

The majority of the mortality in ecoregion 332A–Northeastern Glaciated Plains (MRATIO = 0.86) of North Dakota was split between the cottonwood and aspen (49 percent), white oak (24 percent), and other eastern soft hardwoods (18 percent) species groups. About 37 percent of

Table 5.2—Ecoregion sections in Eastern and Central States having the highest mortality relative to growth (MRATIO), annual mortality and growth rates, and associated causes of mortality

Ecoregion section	Average annual mortality	Average annual gross growth	MRATIO	Major causes of mortality
	------- *cubic feet per year* -------			
M334A–Black Hills	49,178,883	37,114,310	1.33	Insects (76%), fire (14%)
331F–Western Great Plains	12,075,815	12,396,781	0.97	Fire (64%), weather-related (19%)
255C–Oak Woods and Prairies	133,746,975	140,657,294	0.95	Weather-related (67%), disease (18%)
332A–Northeastern Glaciated Plains	8,025,426	9,296,699	0.86	Weather-related (37%), animals (13%)
321B–Stockton Plateau	8,149,276	9,953,146	0.82	Weather-related (69%), fire (30%)
331M–Missouri Plateau	6,393,366	8,777,223	0.73	Weather-related (71%)
332C–Nebraska Sand Hills	10,008,123	14,059,636	0.71	Insects (36%)
332D–North-Central Great Plains	7,993,301	11,460,800	0.70	Fire (39%), insects (19%), disease (18%)
222U–Lake Whittlesey Glaciolacustrine Plain	44,588,109	67,460,158	0.66	Insects (67%)
222H–Central Till Plains-Beech-Maple	111,024,790	176,893,434	0.63	Insects (51%)

the mortality overall (table 5.2) and 38 percent of cottonwood/aspen (*Populus* spp.) mortality was related to adverse weather. North Dakota experienced numerous storm events over the past several years, including 435 hail events and 66 tornadoes during the 2015 and 2016 growing seasons. Damage due to hail storms can make trees susceptible to a number of fungal diseases (North Dakota Forest Service 2015, 2016). Cottonwood canker fungi have been identified as a problem throughout North Dakota (North Dakota Forest Service 2014, 2015); these fungi may be contributing to the observed cottonwood mortality. About 13 percent of mortality was attributed to animals; almost all of this occurred in the cottonwood/aspen species group.

In ecoregion 331M–Missouri Plateau (MRATIO = 0.73), about 72 percent of the mortality (by volume) occurred in the cottonwood and aspen species group. About 71 percent of total mortality (table 5.2) and 90 percent of cottonwood/aspen mortality was identified as weather-related. Adverse weather conditions, including both drought and excessively wet conditions, occurred during the remeasurement cycle (Ball and others 2017; Johnson 2017; North Dakota Forest Service 2012, 2013; South Dakota Department of Agriculture 2012). Multiple tree-damaging storm events, including both hail storms and tornadoes, also occurred over that period (Johnson 2017, North Dakota Forest Service

2016). As mentioned above, cottonwood canker fungi have been identified as a problem throughout North Dakota (North Dakota Forest Service 2014, 2015) and may be contributing to the observed cottonwood mortality.

In ecoregion 332C–Nebraska Sand Hills (MRATIO = 0.71), about 45 percent of the mortality occurred in the cottonwood and aspen species group. About 36 percent of total mortality (table 5.2) and 30 percent of cottonwood/aspen mortality was due to insects. However, the cause of the majority of overall mortality (51 percent) as well as cottonwood/aspen mortality (68 percent) was classified as "unknown/other."

In 332D–North-Central Great Plains (MRATIO = 0.70), 39 percent of mortality was due to fire, while insects were responsible for 19 percent of mortality, and 18 percent of mortality was attributed to diseases (table 5.2). Mortality was high in multiple species groups, including the white oak, ponderosa and Jeffrey pine, other eastern softwoods, and other eastern soft hardwoods species groups. The majority of oak (*Quercus* spp.) and pine mortality was due to fire (74 percent and 65 percent, respectively). Disease was the major cause of mortality in the other eastern soft hardwoods species group (63 percent of mortality). A number of agents may have contributed to the mortality, including oak decline, which has been reported in northern and eastern Nebraska (Nebraska Forest Service 2017, 2018), bur oak blight (*Tubakia iowensis*), and Dutch elm disease (*Ophiostoma novo-ulmi*) (Ball and others 2017, 2018).

Mortality relative to growth was also rather high (MRATIO = 0.66) in ecoregion section 222U–Lake Whittlesey Glaciolacustrine Plain. There, the majority of the mortality (67 percent) was ash (*Fraxinus* spp.). About 67 percent of mortality in that ecoregion section was caused by insects (table 5.2), and insects were responsible for 98 percent of ash mortality. Most of this mortality was due to emerald ash borer (*Agrilus planipennis*), which has produced extremely high ash mortality throughout Ohio and Michigan (Michigan Department of Natural Resources 2014, 2015, 2016, 2017; Ohio Department of Natural Resources, Division of Forestry 2014, 2015). In fact, emerald ash borer has caused the death of the "vast majority" of native ash in northwestern Ohio (Ohio Department of Natural Resources, Division of Forestry 2016, 2017).

Similarly, in the adjacent ecoregion section 222H–Central Till Plains-Beech-Maple (MRATIO = 0.63) in Ohio and Indiana, much of the mortality (53 percent) was ash, and 96 percent of ash mortality was due to insects (table 5.2), most likely emerald ash borer. Indeed, emerald ash borer has been confirmed throughout the ecoregion as well as throughout Indiana (Marshall, 2017, 2018; Ohio Department of Natural Resources, Division of Forestry 2016, 2017). For species other than ash, the mortality-causing agent was most frequently not identified.

Ecoregion section 255C–Oak Woods and Prairies in Texas also had relatively high mortality (MRATIO = 0.95). About 49 percent of the mortality occurred in the red and white oak species groups, and another 18 percent occurred in the loblolly and shortleaf pine species group. The majority (67 percent) of mortality in this ecoregion section was identified as weather-related (table 5.2). Weather was responsible for 72 percent of oak mortality and 43 percent of pine mortality. A record-setting drought in 2011 affected Oklahoma and Texas (Oklahoma Forestry Services 2014, 2015, 2016). It was reported as weakening both pines and hardwoods in Texas, making them susceptible to a variety of pests and pathogens (Smith 2013, 2014). Disease was the reported cause of another 18 percent of mortality (table 5.2). Disease was reported as responsible for 24 percent of oak mortality; fire was responsible for 41 percent of pine mortality. Oak wilt has been a major problem in oak woodlands in central Texas (Smith 2014; Texas A&M Forest Service 2015, 2016, 2019) and probably contributed to the red and white oak mortality. Pine engraver beetle (*Ips* spp.) has been a problem in Texas' pine forests and may have contributed to mortality in the loblolly and shortleaf pine species group (Smith 2014; Texas A & M Forest Service 2015, 2016, 2017).

In ecoregion 321B–Stockton Plateau (MRATIO = 0.82), 69 percent of mortality was related to adverse weather, and another 30 percent was due to fire (table 5.2). About 89 percent of mortality occurred in the western woodland softwoods species group. Most of this mortality probably was related to the previously discussed drought that affected Texas beginning in 2011.

Western States

As mentioned above, in all Western States, less than the full panel of plots have been remeasured. Thus, the mortality results presented here should be considered preliminary. Also, one must be aware that, because of the longer 10-year measurement cycle in the West, results shown represent mortality that may have occurred any time during the period spanned by the data (see table 5.1), which may have been as long as 18 years.

For a large portion of the West, no MRATIO has been presented. At the time this chapter was being written, the Interior West FIA region used a different method for estimating growth than the rest of the country. Thus, MRATIOs calculated for Interior West States were not comparable to values from the rest of the country, and no MRATIOs were presented for ecoregions in those States. MRATIOs were also not calculated for some ecoregions in West Coast States. This was because either (1) fewer than 25 plots had been remeasured in an ecoregion, or (2) the percent sampling error for the growth estimate was too high (>100 percent). Aside from the Interior West region, ecoregions omitted from the analysis were mostly nonforest (mostly desert or grassland, heavily urbanized, or mostly converted to agriculture).

West Coast ecoregion sections having the highest MRATIOs are shown in table 5.3 with the major causes of death identified. Seeing that fire and weather as well as insects and disease

Table 5.3—Ecoregion sections in West Coast States having the highest mortality relative to growth (MRATIO), annual mortality and growth rates, and associated causes of mortality

Ecoregion section	Average annual mortality	Average annual gross growth	MRATIO	Major causes of mortality
	------- *cubic feet per year* -------			
M262B–Southern California Mountain and Valley	30,749,476	13,564,463	2.27	Fire (67%), insects (10%), weather-related (10%)
341D–Mono	6,800,601	9,241,166	0.74	Insects (44%), fire (35%), disease (15%)
M242D–Northern Cascades	341,346,926	469,304,231	0.73	Insects (32%), fire (25%), weather-related (16%), disease (16%)
M261E–Sierra Nevada	435,027,997	641,958,197	0.68	Fire (32%), disease (30%), weather-related (12%), insects (13%)
M261C–Northern California Interior Coast Ranges	5,272,704	7,881,888	0.67	Fire (46%), disease (26%), weather-related (12%)
M261F–Sierra Nevada Foothills	20,425,732	32,442,906	0.63	Disease (20%), weather-related (16%), fire (12%)
M262A–Central California Coast Ranges	6,021,453	9,629,495	0.63	Disease (33%), fire (22%), weather-related (15%)

were responsible for significant mortality in these West Coast ecoregion sections, mortality was summarized by both forest type group and species group. One would expect that patterns of mortality caused by biotic factors (insects, disease) would be most apparent when looking at species groups affected, while patterns of mortality caused by abiotic factors (weather, fire) would be most apparent when looking at forest types affected.

Of the ecoregion sections of the West Coast States where the MRATIO could be calculated, ecoregion section M262B–Southern California Mountain and Valley (MRATIO = 2.27) stands out. This is the highest MRATIO found anywhere in the United States. Fire was responsible for 67 percent of this mortality (table 5.3). Insects were responsible for 10 percent of mortality, and adverse weather was responsible for another 10 percent. About 57 percent of the mortality in this ecoregion section occurred in the Western Oak forest type group, and most of that mortality (79 percent) was due to fire. Fire was also responsible for most of the mortality (76 percent) in the Pinyon/juniper forest type group, where 7 percent of the ecoregion's mortality occurred. Insects were responsible for almost all the mortality in the Ponderosa Pine forest type group and about 43 percent of the mortality in the California Mixed Conifer forest type group; they were responsible for about 21 percent of the mortality in the ponderosa and Jeffrey pine species group and about 17 percent of the other western softwoods species group.

In ecoregion section 341D–Mono (MRATIO = 0.74), about 64 percent of mortality occurred in the western woodland softwoods species group, and about 21 percent was lodgepole pine (*P. contorta*). All of the lodgepole pine mortality was attributed to insects, while for western woodland softwoods, about 49 percent of mortality was due to fire, about 28 percent was due to insects, and 19 percent was due to disease.

In M261E–Sierra Nevada (MRATIO = 0.68), mortality occurred in a large number of species groups, with the highest mortality suffered by true firs (43 percent), ponderosa and Jeffrey pine (17 percent), and sugar pine (11 percent). A variety of agents (insects, disease, fire, and weather) contributed to the observed mortality. Disease was the single most important cause of mortality in the true firs and sugar pine.

In M261C–Northern California Interior Coast Ranges (MRATIO = 0.67), almost all of the mortality occurred in the Western Oak forest type group (which does not include tanoak-dominated forest types). About 41 percent of the mortality was oaks, and about 54 percent was the other western softwoods species group. About 52 percent of the oak mortality and about 40 percent of the softwood mortality was due to fire. Another 40 percent of softwood mortality was attributed to disease.

Similarly, in M261F–Sierra Nevada Foothills (MRATIO = 0.63), almost all of the mortality occurred in the Western Oak forest type group. About 65 percent of the mortality was oaks, about 17 percent was other western softwoods, and 8 percent was ponderosa/Jeffrey pine. However, in this ecoregion section, a variety of agents (disease, fire, and weather) all contributed to the observed mortality (table 5.3).

Likewise, in ecoregion section M262A–Central California Coast Ranges (MRATIO = 0.63), almost all of the mortality occurred in the Western Oak forest type group. About 81 percent of the mortality was oaks. In this ecoregion section, disease was responsible for 33 percent of mortality, fire caused 22 percent of mortality, and 15 percent of mortality was attributed to adverse weather (table 5.3).

At a broad scale, we see that in much of California tree mortality is often related to a combination of prolonged drought (2011–2015 statewide; 2011–2017 in parts of the State), bark beetles, and fire (California Forest Pest Council 2015, 2016, 2017). These factors have interacted, leading to high mortality, especially in southern California. Overstocked stands in many parts of the State have contributed to the drought stress and susceptibility of forests to insects and wildfires (California Forest Pest Council 2015, 2016, 2017). It should also be noted that the same drought which led to high mortality (directly or indirectly) would also have reduced growth over the measurement period; reduced growth also contributes to a high MRATIO (see Methods section).

Aside from California, the highest MRATIO (0.73) occurred in ecoregion section M242D–Northern Cascades. There, mortality occurred in a large number of species groups, including

Engelmann and other spruces (22 percent), true firs (24 percent), lodgepole pine (15 percent), and Douglas-fir (17 percent). While insects and fire were the most significant mortality-causing agents, other factors, including disease and adverse weather, also contributed significantly to the observed mortality (table 5.3).

Figure 5.3 shows the ratio of annual mortality to standing live tree volume for the United States. In most of the country, the ecoregions having high mortality relative to standing volume are the same regions that had high MRATIOs (fig. 5.2).

Focusing on the Interior West, we see two clusters of ecoregion sections where mortality is high relative to standing live volume: a cluster of mountain ecoregion sections in western Montana, central Idaho, and northwestern Wyoming (M331A–Yellowstone Highlands, M331J–Wind River Mountains, M332A–Idaho Batholith, M332B–Northern Rockies and Bitterroot Valley, M332D–Belt Mountains, M332E–Beaverhead Mountains, and M332F–Challis Volcanics) and a cluster including the Front Range of Colorado and southern Wyoming (M331I–Northern Parks and Ranges) and the south-central highlands of Colorado and northern New Mexico (M331G–South-Central Highlands) together with the Uinta Mountains of Utah (M331E–Uinta Mountains). In all of these ecoregion sections, annual mortality exceeded 2.5 percent of live volume (table 5.4).

In Colorado and Wyoming, 61 percent of the mortality in ecoregion section M331I–Northern Parks and Ranges was lodgepole pine, and another 20 percent was the Engelmann and other spruces species group; almost all of this mortality was attributed to insects. The ecoregion includes areas that have experienced major outbreaks of mountain pine beetle as well as spruce beetle (*D. rufipennis*) (Colorado State Forest Service 2016; Wyoming State Forestry Division 2016, 2017). These same pests have been affecting ecoregion M331E–Uinta Mountains (USDA Forest Service, Uinta-Wasatch-Cache National Forest [N.d.], Utah Department of Natural Resources, Forestry, Fire, & State Lands 2016), where 62 percent of mortality was lodgepole pine, and 18 percent was the Engelmann and other spruces species group. Here, also, most of the mortality was caused by insects. In ecoregion section M331G–South-Central Highlands, about two-thirds of mortality overall was caused by insects. In this ecoregion section, about 64 percent of mortality was the Engelmann and other spruces species group; 88 percent of spruce mortality was due to insects. In this area, spruce beetle has caused significant mortality (Colorado State Forest Service 2016, 2017; Zegler 2015, 2016; Zegler and Formby 2017).

In the areas of high mortality in Montana, Idaho, and northwestern Wyoming (ecoregion sections M331A, M331J, M332A, M332B, M332D, M332E, and M332F), insects and fire

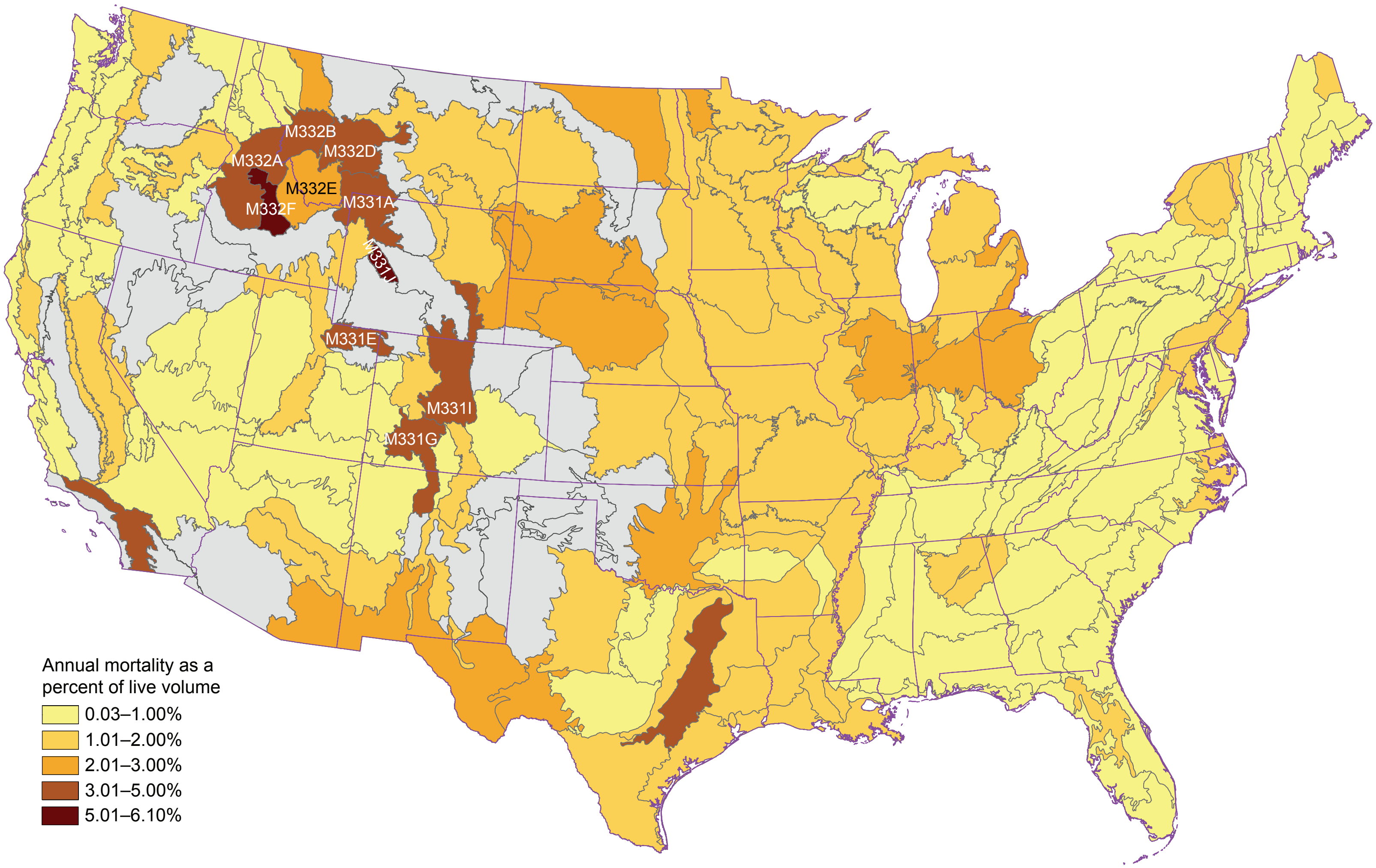

Figure 5.3—Annual tree mortality expressed as a percentage of live tree volume by ecoregion section (Cleland and others 2007). Data unavailable or insufficient for gray areas. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis program)

Table 5.4—Ecoregion sections in Interior West States having the highest mortality relative to standing tree volume and associated causes of mortality

Ecoregion section	Average annual mortality	Standing tree volume	Mortality relative to standing volume	Major causes of mortality
	cubic feet per year	*cubic feet*		
M332F–Challis Volcanics	130,337,369	2,137,789,144	6.10%	Fire (51%), insects (40%)
M331J–Wind River Mountains	51,284,166	950,316,430	5.40%	Insects (69%), fire (20%)
M332D–Belt Mountains	203,919,686	4,906,754,034	4.16%	Insects (87%)
M331I–Northern Parks and Ranges	514,041,199	12,391,505,232	4.15%	Insects (84%)
M331A–Yellowstone Highlands	327,715,284	8,192,840,314	4.00%	Insects (57%), fire (27%)
M331E–Uinta Mountains	103,858,588	2,766,471,956	3.75%	Insects (72%), disease (17%)
M331G–South-Central Highlands	326,038,823	9,383,451,487	3.47%	Insects (67%), fire (13%), disease (11%)
M332B–Northern Rockies and Bitterroot Valley	191,975,434	5,921,485,532	3.24%	Insects (50%), fire (36%)
M332A–Idaho Batholith	532,620,433	17,627,954,803	3.02%	Fire (55%), insects (25%), disease (11%)
M332E–Beaverhead Mountains	149,432,898	5,317,108,378	2.81%	Insects (76%), fire (15%)

were the most significant causes of mortality (table 5.4). This region includes areas suffering outbreaks of mountain pine beetle (Montana Department of Natural Resources and Conservation 2014, 2016) as well as major fires (Idaho Department of Lands 2014). However, several other insect and disease issues have been identified in this region and may have contributed to the mortality. In most of these ecoregion sections (M331A, M331J, M332A, M332B, M332D, M332E), lodgepole pine was the species suffering the highest mortality, most of which was due to insects. However, many other species groups, including Douglas-fir, true firs, and Engelmann and other spruces also suffered non-trivial mortality.

SUMMARY

This analysis shows that in most of the Eastern and Central United States, mortality is low relative to tree growth. The areas of highest mortality occur in the mostly riparian forests of Great Plains ecoregions. A common characteristic of most of the ecoregions having high mortality is that they are on the margins of land suitable for forest growth, being very dry. Thus, they tend to be extremely vulnerable to changes in weather patterns that might produce prolonged and/or extreme drought. Drought, combined with a variety of other biotic and/or abiotic stressors, is likely responsible for much of the mortality observed.

However, one insect pest issue does stand out in the East. In ecoregions 222H–Central Till Plains-Beech-Maple and 222U–Lake Whittlesey Glaciolacustrine Plain, ash mortality due to emerald ash borer was extremely high.

The preliminary analysis of the Western United States shows that, in many parts of the Interior West, mortality is very high as a percentage of live volume and that several West Coast ecoregion sections have high MRATIOs. All of these areas correspond to regions where insect outbreaks (see ch. 2) as well as fire (ch. 3) and/or severe drought (ch. 4) have occurred. These three mortality-causing agents are related in that drought stresses trees, making them more susceptible to insect attack, while both drought and insect-killed trees create conditions favorable for wildfires.

It is also important to realize that the analyses presented in this chapter alone cannot tell the complete story regarding tree mortality. Mortality that is concentrated in highly fragmented forest or nonforest areas adjacent to human development may not be detected because the available FIA data do not cover most urban areas or other places not defined as forest by FIA. Also, these analyses are unlikely to detect a pest or pathogen attacking a particular tree species in a mixed-species forest where other species are growing vigorously. This is especially true of species (e.g., ash) that make up a relatively small proportion of many eastern forests. For example, it is known that emerald ash borer has been causing very high ash mortality in many Eastern and Central States in recent years (Ohio Department of Natural Resources, Division of Forestry 2016; USDA APHIS 2018), yet this mortality stands out only in ecoregions 222H–Central Till Plains-Beech-Maple and 222U–Lake Whittlesey Glaciolacustrine Plain. Elsewhere in the East, though ash mortality is known to be extremely high, the mortality is masked because ash is a relatively minor component of the forest.

To gain a more complete understanding of mortality, one should consider the results of this analysis together with other indicators of forest health. Forest Inventory and Analysis tree damage data (Burrill and others 2018), as well as Evaluation Monitoring projects that focus on particular mortality-causing agents (ch. 8–13) can provide insight into smaller scale or species-specific mortality issues. Large-scale analyses of forest-damaging events, including insect and disease activity (ch. 2) and fire (ch. 3) are also important for understanding mortality patterns. This can be especially important in the West, where mortality data are limited.

LITERATURE CITED

Ball, J.; Pyser, N.; Warnke, M. 2016. Forest health highlights in South Dakota 2016. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 6 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: May 9, 2018].

Ball, J.; Seidl, A.; Warnke, M. 2017. State of South Dakota forest health highlights. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 8 p. https://sdda.sd.gov/conservation-forestry/forest-health/SDHighlights_2017-2.pdf. [Date accessed: July 23, 2019].

Ball, J.; Seidl, A.; Warnke, M. 2018. State of South Dakota forest health highlights. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 12 p. https://sdda.sd.gov/conservation-forestry/forest-health/SDHighlights_2018.pdf. [Date accessed: July 1, 2019].

Ball, J.; Warnke, M.; Garbisch, B. 2015. Forest health highlights in South Dakota 2015. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 9 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: May 9, 2018].

Bechtold, W.A.; Patterson, P.L., eds. 2005. The enhanced Forest Inventory and Analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Burrill, E.A.; Wilson, A.M.; Turner, J.A. [and others]. 2018. The Forest Inventory and Analysis Database: database description and user guide for Phase 2 (version 8.0). Washington, DC: U.S. Department of Agriculture Forest Service. 946 p. http://fia.fs.fed.us/library/database-documentation/. [Date accessed: July 16, 2019].

California Forest Pest Council. 2015. 2015 California forest health highlights. 21 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: July 9, 2018].

California Forest Pest Council. 2016. 2016 California forest health highlights. 31 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: May 9, 2018].

California Forest Pest Council. 2017. 2017 California forest health highlights. 38 p. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd578578.pdf. [Date accessed: May 9, 2018].

Cleland, D.T.; Freeouf, J.A.; Keys, J.E. [and others]. 2007. Ecological subregions: sections and subsections for the conterminous United States. Gen. Tech. Rep. WO-76D. Washington, DC: U.S. Department of Agriculture Forest Service. Map; Sloan, A.M., cartographer; presentation scale 1:3,500,000; colored. Also on CD-ROM as a GIS coverage in ArcINFO format.

Colorado State Forest Service. 2016. 2015 report on the health of Colorado's forests: 15 years of change. Fort Collins, CO: Colorado State Forest Service. 32 p. https://csfs.colostate.edu/media/sites/22/2016/02/ForestHealthReport-2015.pdf. [Date accessed: July 30, 2019].

Colorado State Forest Service. 2017. 2016 report on the health of Colorado's forests: fire and water. Fort Collins, CO: Colorado State Forest Service. 36 p. https://csfs.colostate.edu/media/sites/22/2017/02/CSU_304464_ForestReport-2016-www.pdf. [Date accessed: July 30, 2019].

Coulston, J.W.; Ambrose, M.J.; Stolte. K.S. [and others]. 2005. Criterion 3 – health and vitality. In: Conkling, B.L.; Coulston, J.W.; Ambrose, M.J., eds. Forest Health Monitoring 2001 national technical report. Gen. Tech. Rep. SRS-81. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 204 p.

Idaho Department of Lands. 2014. 2014 forest health highlights. 7 p. https://www.fs.fed.us/foresthealth/docs/fhh/ID_FHH_2014.pdf. [Date accessed: July 30, 2019].

Johnson, L. 2017. North Dakota forest health highlights 2017. 12 p. https://www.ag.ndsu.edu/ndfs/documents/north-dakota-forest-health-highlights-2017.pdf. [Date accessed: July 23, 2019].

Marshall, P.T. 2017. 2017 Indiana forest health highlights. Vallonia, IN: Indiana Department of Natural Resources. 17 p. https://www.in.gov/dnr/forestry/files/fo-Forest_Health_Highlights_2017.pdf. [Date accessed: June 20, 2019].

Marshall, P.T. 2018. 2018 Indiana forest health highlights. Vallonia, IN: Indiana Department of Natural Resources. 17 p. https://www.in.gov/dnr/forestry/files/fo-Forest_Health_Highlights_2018.pdf. [Date accessed: June 20, 2019].

McNab, W.H.; Cleland, D.T.; Freeouf, J.A. [and others], comps. 2007. Description of ecological subregions: sections of the conterminous United States. [CD-ROM]. Gen. Tech. Report WO-76B. Washington, DC: U.S. Department of Agriculture Forest Service. 80 p. https://doi.org/10.2737/WO-GTR-76B.

Michigan Department of Natural Resources. 2014. 2014 forest health highlights. 51 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 27, 2018].

Michigan Department of Natural Resources. 2015. 2015 forest health highlights. 50 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 8, 2018].

Michigan Department of Natural Resources. 2016. 2016 forest health highlights. 51 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 8, 2018].

Michigan Department of Natural Resources. 2017. 2017 forest health highlights. 31 p. https://www.michigan.gov/documents/dnr/frsthlthhghlghts_513144_7.pdf. [Date accessed: May 8, 2018].

Montana Department of Natural Resources and Conservation, Forest Pest Management Program. 2014. Montana forest health highlights 2014. 4 p. https://www.fs.fed.us/foresthealth/docs/fhh/MT_FHH_2014.pdf. [Date accessed: July 30, 2019].

Montana Department of Natural Resources and Conservation, Forest Pest Management Program. 2016. Montana forest health highlights 2016. 4 p. http://dnrc.mt.gov/divisions/forestry/docs/assistance/pests/conditions-highlights/fhh_2016.pdf. [Date accessed: July 30, 2019].

Nebraska Forest Service. 2017. Nebraska forest health highlights 2017. 6 p. https://www.fs.fed.us/foresthealth/docs/fhh/NE_FHH_2017.pdf. [Date accessed: August 25, 2018].

Nebraska Forest Service. 2018. Nebraska forest health highlights 2018. 3 p. https://nfs.unl.edu/publications/downloads/NE2018Forest%20Health%20Highlights-3.pdf. [Date accessed: July 12, 2019].

North Dakota Forest Service. 2012. North Dakota forest health highlights 2012. 12 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: May 15, 2018].

North Dakota Forest Service. 2013. North Dakota forest health highlights 2013. 12 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 26, 2018].

North Dakota Forest Service. 2014. North Dakota forest health highlights 2014. 24 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 12, 2018].

North Dakota Forest Service. 2015. North Dakota forest health highlights 2015. 24 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 12, 2018].

North Dakota Forest Service. 2016. North Dakota forest health highlights 2016. 4 p. https://www.ag.ndsu.edu/ndfs/documents/north-dakota-forest-health-highlights-2016.pdf. [Date accessed: August 25, 2018].

Ohio Department of Natural Resources, Division of Forestry. 2014. 2014 Ohio forest health highlights. 7 p. Columbus, OH: Ohio Department of Natural Resources, Division of Forestry. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 27, 2018].

Ohio Department of Natural Resources, Division of Forestry. 2015. 2015 Ohio forest health highlights. 8 p. Columbus, OH: Ohio Department of Natural Resources, Division of Forestry. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 17, 2018].

Ohio Department of Natural Resources, Division of Forestry. 2016. 2016 Ohio forest health highlights. 8 p. Columbus, OH: Ohio Department of Natural Resources, Division of Forestry. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 17, 2018].

Ohio Department of Natural Resources, Division of Forestry. 2017. 2017 Ohio forest health highlights. 7 p. Columbus, OH: Ohio Department of Natural Resources, Division of Forestry. https://www.fs.fed.us/foresthealth/docs/fhh/OH_FHH_2017.pdf. [Date accessed: July 7, 2019].

Oklahoma Forestry Services. 2014. Oklahoma forest health highlights 2014. 5 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 2, 2018].

Oklahoma Forestry Services. 2015. Oklahoma forest health highlights 2015. 6 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 3, 2018].

Oklahoma Forestry Services. 2016. Oklahoma forest health highlights 2016. 6 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 2, 2018].

Pugh, S.A.; Turner, J.A.; Burrill, E.A.; David, W. 2018. The Forest Inventory and Analysis Database: population estimation user guide (edition: November 2018). U.S. Department of Agriculture Forest Service. 166 p. http://www.fia.fs.fed.us/library/database-documentation/. [Date accessed: July 25, 2020].

Smith, L.A. 2013. Forest health insects and diseases conditions Texas 2013. Longview, TX: Texas A & M Forest Service. 5 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 27, 2018].

Smith, L.A. 2014. Forest health highlights in Texas 2014. Longview, TX: Texas A & M Forest Service. 1 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 27, 2018].

South Dakota Department of Agriculture. 2011. South Dakota forest health highlights 2011. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 4 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: May 1 2018].

South Dakota Department of Agriculture. 2012. South Dakota 2012 forest health highlights. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 5 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: March 15, 2018].

South Dakota Department of Agriculture. 2013. South Dakota 2013 forest health highlights. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 5 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: March 15, 2018].

South Dakota Department of Agriculture. 2014. South Dakota 2014 forest health highlights. Pierre: South Dakota Department of Agriculture, Division of Resource Conservation and Forestry. 7 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: March 15, 2018].

Texas A & M Forest Service. 2015. Forest health highlights in Texas 2015. Longview, TX: Texas A & M Forest Service. 1 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 20, 2018].

Texas A & M Forest Service. 2016. Forest health highlights in Texas 2016. Longview, TX: Texas A & M Forest Service. 1 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 20, 2018].

Texas A & M Forest Service. 2017. Forest health highlights 2017. Longview, TX: Texas A & M Forest Service. 2 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: May 21, 2018].

Texas A & M Forest Service. 2019. Forest health highlights 2019. Longview, TX: Texas A & M Forest Service. 2 p. https://www.fhm.fs.fed.us/foresthealth/docs/fhh/TX_FHH_2019.pdf. [Date accessed: May 21, 2020].

U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS). 2018. Emerald ash borer. https://www.aphis.usda.gov/aphis/resources/pests-diseases/hungry-pests/the-threat/emerald-ash-borer/emerald-ash-borer-beetle. [Date accessed: August 31, 2018].

U.S. Department of Agriculture (USDA) Forest Service. 2008. National forest type dataset. [Online]. http://data.fs.usda.gov/geodata//rastergateway/forest_type/index.php. [Date accessed: September 13, 2016].

U.S. Department of Agriculture (USDA) Forest Service, Forest Inventory and Analysis (FIA) program. 2019. Forest Inventory EVALIDator web-application version 1.8.0.01 St. Paul, MN: U.S. Department of Agriculture Forest Service, Northern Research Station. http://apps.fs.fed.us/Evalidator/evalidator.jsp. [Date accessed: July 13, 2020].

U.S. Department of Agriculture (USDA) Forest Service, Uinta-Wasatch-Cache National Forest. [N.d.]. Beetle activity on the Uinta-Wasatch-Cache National Forest. http://www.fs.usda.gov/detail/uwcnf/home/?cid=STELPRDB5145143. [Date accessed: July 25, 2017].

Utah Department of Natural Resources, Forestry, Fire, & State Lands. 2016. Utah forest health highlights 2016. 3 p. https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. [Date accessed: April 24, 2018].

Wyoming State Forestry Division. 2016. 2016 Wyoming forest health highlights. 16 p. https://www.fs.fed.us/foresthealth/docs/fhh/WY_FHH_2016.pdf. [Date accessed: August 25, 2018].

Wyoming State Forestry Division. 2017. 2017 Wyoming forest health highlights. 17 p. https://www.fs.fed.us/foresthealth/docs/fhh/WY_FHH_2017.pdf. [Date accessed: August 25, 2018].

Zegler, T. 2015. New Mexico forest health conditions, 2015. 17 p. http://www.emnrd.state.nm.us/SFD/FWHPlan/documents/2015_NMconditionsreport_low_shortIIpdf.pdf. [Date accessed: July 30, 2019].

Zegler, T. 2016. New Mexico forest health conditions, 2016. 18 p. http://www.emnrd.state.nm.us/SFD/FWHPlan/documents/2016_NMconditionsreport_short.pdf. [Date accessed: July 30, 2019].

Zegler, T.; Formby, J.P. 2017. New Mexico forest health conditions 2017. 35 p. http://www.emnrd.state.nm.us/SFD/FWHPlan/documents/NMForestHealthConditionsReportComplete.pdf. [Date accessed: July 30, 2019].